

MECHANICAL PROPERTIES AND FRACTURE BEHAVIOUR OF PROTAC 500 ARMOUR STEEL

MEHANIČKA SVOJSTVA I PONAŠANJE PRI LOMU PANCIRNOG ČELIKA PROTAC 500

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Keywords

- mechanical properties
- fracture mechanics
- fatigue crack growth
- armour steel

Abstract

Knowledge of mechanical properties, fracture toughness, and fatigue crack growth is a crucial prerequisite for the reliable and safe application of armour steel in protective structures. This study presents an experimental characterisation of PROTAC 500 armour steel, produced by heat treatment by low-temperature tempering at 220 °C. Mechanical testing included hardness measurement, tensile testing, and impact toughness evaluation. The measured hardness is 533 HV, while tensile testing reveals a tensile strength of 1677 MPa. The Charpy impact toughness reaches 42 J/cm², indicating a favourable combination of high strength and resistance to fracture. Fracture toughness is determined in accordance with the ASTM E1820 standard using the unloading compliance method with value of 105 MPa·m^{1/2}. The fatigue crack growth behaviour is analysed using the Paris and McEvily law, with a determined threshold for crack propagation $\Delta K_{th} = 7.87 \text{ MPa} \cdot \text{m}^{1/2}$. Obtained results provide a reliable assessment of the material behaviour under both static and cyclic loading conditions. Through comprehensive evaluation of mechanical and fracture parameters, a complete characterisation of the armour steel is achieved.

INTRODUCTION

Knowing the mechanical properties, fracture toughness and fatigue crack growth rate of the material is a basic assumption for evaluating the mechanical response and lifetime of structures exposed to static and dynamic loads. Mechanical properties, including strength and hardness, directly affect the bearing capacity and resistance of materials to deformation, while fracture toughness enables a quantitative assessment of the material ability to absorb energy before breaking. Fatigue crack growth rate under cyclic loading further expands the understanding of material behaviour during exploitation and enables a reliable assessment of its remaining life, /1-3/.

The need for a comprehensive characterisation of these properties is especially pronounced for armour steels used in protective structures, where the reliability of the properties has a direct impact on the safety and efficiency of the structures. Armour steels belong to the group of high-strength

Ključne reči

- mehaničke osobine
- mehanika loma
- rast zamorne prsline
- pancirni čelik

Izvod

Poznavanje mehaničkih osobina, žilavosti loma i rast zamorne prsline predstavlja ključni preduslov za pouzdanu i bezbednu primenu pancirnih čelika u zaštitnim konstrukcijama. U ovom radu izvršena je eksperimentalna karakterizacija pancirnog čelika PROTAC 500, proizvedenog termičkom obradom niskotemperaturnim otpuštanjem na 220 °C. Mehanička ispitivanja obuhvatila su određivanje tvrdoće, zateznih osobina i udarne žilavosti. Izmerena tvrdoća iznosi 533 HV, dok je ispitivanjem zatezanjem dobijena zatezna čvrstoća od 1677 MPa. Charpy udarna žilavost materijala iznosi 42 J/cm², što ukazuje na povoljnu kombinaciju čvrstoće i otpornosti na lom. Žilavost loma određena je prema standardu ASTM E1820 metodom popuštanja i iznosi 105 MPa·m^{1/2}. Ponašanje rasta zamorne prsline je analizirano primenom Parisovog i McEvily zakona, pri čemu je utvrđen prag za rast prsline $\Delta K_{th} = 7,87 \text{ MPa} \cdot \text{m}^{1/2}$. Dobijeni rezultati omogućavaju pouzdanu procenu ponašanja materijala u uslovima statičkog i cikličnog opterećenja. Sveobuhvatnom analizom mehaničkih parametara i parametara loma, izvršena je kompletna karakterizacija pancirnog čelika.

steels that require an optimal combination of strength, hardness and toughness to meet the strict requirements of ballistic protection and minimise the weight of the structure. Their primary function is to provide impenetrability and protection against ballistic threats, /4-6/.

PROTAC 500 material belongs to this group of armour steels and is produced in the Slovenian iron factory SIJ Acroni d.o.o. in Jesenice, using different heat treatments that include hardening and tempering in order to achieve appropriate mechanical properties.

PROTAC 500 has been the subject of many studies: Bertenič et al. /7/ investigated mechanical properties, Čabrilo et al. /8/ investigated the influence of welding on mechanical properties, while Trajkovski et al. /9/ described deformations and fracture properties through a combination of experimental and numerical tests.

In this work, the armour steel PROTAC 500 produced by heat treatment with low-temperature tempering at 220 °C is

examined, and the goal is to include complete mechanical and fracture-mechanics tests in order to characterise the material and enable the assessment of its properties and life in working conditions.

MATERIAL

PROTAC 500 is a high-strength and high-hardness armour steel used for protective and armoured applications. It is characterised by a favourable combination of high strength, satisfactory ductility and impact toughness, including work at low temperatures, with good welding and bending properties. Components made of this steel meet the requirements of the relevant ballistic standards (STANAG 4569, AEP55, VPAM PM 2007, etc.), providing a high level of protection against projectile penetration, /10/. The chemical composition of the material is shown in Table 1, while its minimum mechanical properties are shown in Table 2.

Table 1. Chemical composition of PROTAC 500 (wt.%).

C	Si	Mn	P	Cr	Ni	Mo	S
0.30	1.00	0.90	0.01	0.80	1.00	0.40	0.01

Table 2. Minimum mechanical properties of PROTAC 500.

Yield strength $R_{p0.2}$ (MPa)	Tensile strength R_m (MPa)	Elongation A_5 (%)
1200	1600	7.5

In this paper, experimental research is conducted on armour steel PROTAC 500, which is subjected to appropriate heat treatment, consisting of quenching and low-temperature tempering at 220 °C for 3 h (Fig. 1). This heat treatment regime is applied with the aim of achieving an optimal combination of high strength, hardness and satisfactory toughness of the material.

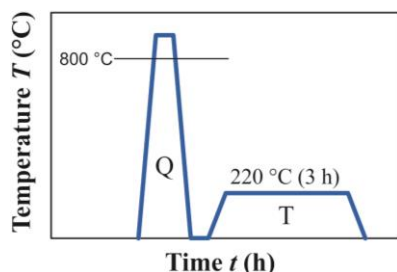


Figure 1. Heat treatment of PROTAC 500.

METHODS

In order to determine the mechanical properties of the tested material, the following tests are carried out: hardness measurement, tensile test and instrumented Charpy test of impact toughness.

Before conducting mechanical testing, a special sample is prepared for the analysis of the material's microstructure. The sample is polished and etched with 3 % nital before being imaged on a Nikon Epiphot 300 light microscope (Nikon Metrology Inc., MI, USA).

Hardness is measured according to the EN ISO 6507-1 standard /11/ using the Vickers method HV 10. The test is carried out on a Roell-Zwick Z600 device (Zwick, Roell Group, Ulm, Germany), where a loading of 98.1 N is applied.

Tensile tests are conducted according to EN ISO 6892-1 standard /12/ on cylindrical specimens with geometry shown in Fig. 2.

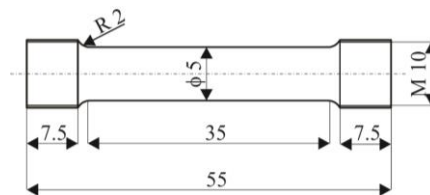


Figure 2. The geometry of the tensile test specimen.

The Charpy impact toughness test is performed according to EN ISO 148-1 /13/ standard using an instrumented Charpy pendulum Amsler RPK 300 (Zwick, Roell Group, Ulm, Germany). The use of the instrumented system enables a detailed analysis of the fracture process, whereby the total absorbed energy is separated into crack initiation energy and crack propagation energy. The geometry of ISO V-notch test specimens used for the Charpy test is shown in Fig. 3.

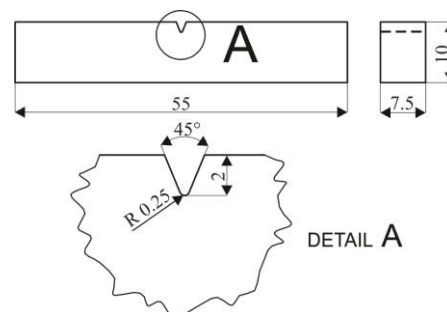


Figure 3. Geometry of the ISO V-notch Charpy test specimen.

Determination of fracture mechanics parameters, including critical J-integral (J_{IC}), critical crack tip opening displacement (CTOD) and stress intensity factor (K_{JIC}), as a measure of fracture toughness, is performed in accordance with ASTM E1820 standard /14/. Testing is conducted using the compliance method. The experimental test is carried out on the Vibrophore 100 tensile machine (Zwick, Roell Group, Ulm, Germany), where the geometry of the SENB (single edge notch bending) specimen is shown in Fig. 4. The VHX-7100 microscope (Keyence NV/SA, Mechelen, Belgium) is used to image the fracture surface and to measure the crack.

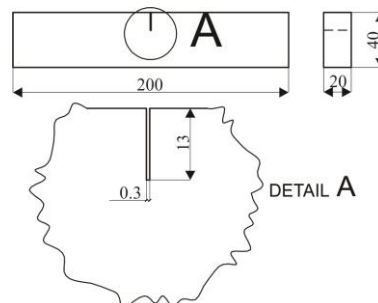


Figure 4. Geometry of SENB specimen for fracture mechanics test.

To describe fatigue crack growth behaviour under cyclic loading, the ASTM E647 standard /15/ is applied. In accordance with the standard, the SENB test specimen is prepared with the geometry as shown in Fig. 5. Based on the experimentally obtained Paris curve, the fatigue crack growth

(da/dN), as a depends on the stress intensity factor ΔK , is characterised using two laws: the Paris law and McEvily law. Testing is carried out on a Rumul Cracktronic testing device (Russenberger Prüfmaschinen AG, Neuhausen, Switzerland), using RMF-A5 crack gauges (Russenberger Prüfmaschinen AG, Neuhausen, Switzerland).

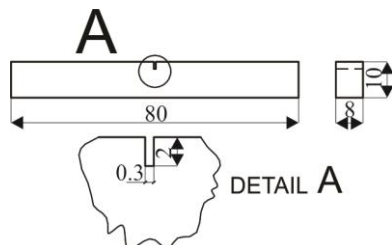


Figure 5. Geometry of SENB specimen for fatigue crack growth test.

RESULTS

Microscopic analysis reveals the microstructure of the PROTAC 500 armour steel. Figure 6 shows the tempered martensitic microstructure (at 500 $\times$ magnification) formed as a result of applied heat treatment, specifically low-temperature tempering.

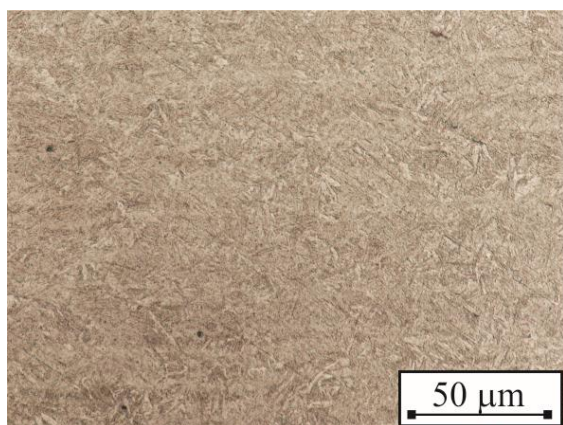


Figure 6. Microstructure of PROTAC 500.

The results of all hardness measurements are presented in Table 3. Furthermore, the average value is converted into the Brinell hardness unit (HB), as the Brinell scale is the standard hardness designation commonly used for armour steels according to relevant specifications.

Table 3. Hardness measurement results.

Point	Hardness (HV 10)	Point	Hardness (HV 10)
1	527	6	533
2	522	7	526
3	543	8	533
4	543	9	539
5	534	10	535
avg.	533.5 HV 10, 504 HB		

As a result of tensile testing, the following parameters are obtained: yield strength $R_{p0.2}$, tensile strength R_m , elongation A_5 , and cross-section contraction Z . The results of the tensile tests are presented in Table 4.

The instrumented Charpy impact toughness test (performed at room temperature) provides the following results: total fracture energy E_t , crack initiation energy E_i , crack

propagation energy E_p , and impact toughness KV. Results of this testing are presented in Table 5.

Table 4. Results of the tensile tests.

Specimen	$R_{p0.2}$ (MPa)	R_m (MPa)	A_5 (%)	Z (%)
1-TT	1303	1678	11.6	52.7
2-TT	1298	1671	11.4	49.8
3-TT	1306	1682	11.8	54.4
Average	1302	1677	11.6	52.3

Table 5. Results of the Charpy tests.

Specimen	E_t (J)	E_i (J)	E_p (J)	KV (J/cm ²)
1-CHT	34.7	25.8	8.9	46.2
2-CHT	31.8	24.7	7.1	42.4
3-CHT	29.5	23.9	5.6	39.3
Average	32.0	24.8	7.2	42.6

Using the compliance method according to ASTM E1820, the specimen was first fatigue pre-cracked in order to obtain a pre-fatigue crack length within the range $0.45 < a_0/W < 0.55$. Subsequently, under continuous load increase, the CMOD (crack mouth opening displacement) was measured using a CMOD gauge. For each CMOD increment of 0.02 mm, unloading is performed in order to obtain as many data points as possible for constructing the J - Δa and δ - Δa resistance curves. The F -CMOD record is shown in Fig. 7.

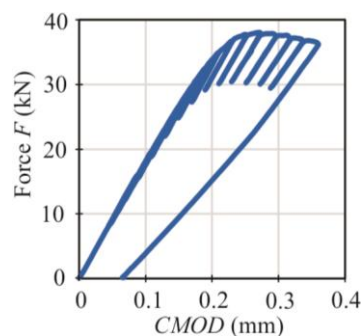


Figure 7. The F -CMOD record.

After completion of the test, the specimen is subjected to post-fatigue cycling in order to induce final fracture. The crack size is measured from the fractured surfaces. Figure 8 shows one of the fracture surfaces of the specimen from which the pre-fatigue crack length a_0 and final crack length after stable crack growth a_f are measured. The point-by-point crack length measurement results are presented in Table 6.

Table 6. Crack measurement.

Point of measurement	Position X (mm)	a_0 (mm)	a_f (mm)
1	0.190	19.608	19.674
2	2.525	19.474	20.075
3	4.860	18.486	21.432
4	7.195	18.462	21.190
5	9.530	19.042	20.704
6	11.864	19.701	21.207
7	14.199	20.529	20.857
8	16.534	21.052	21.200
9	18.869	21.076	21.177
$\Delta a = 1.12$		19.714	20.835

Additionally, a 3D surface profile of the specimen fracture surface is obtained (Fig. 9) using a digital microscope in

order to clearly visualise the fracture morphology and crack propagation behaviour.

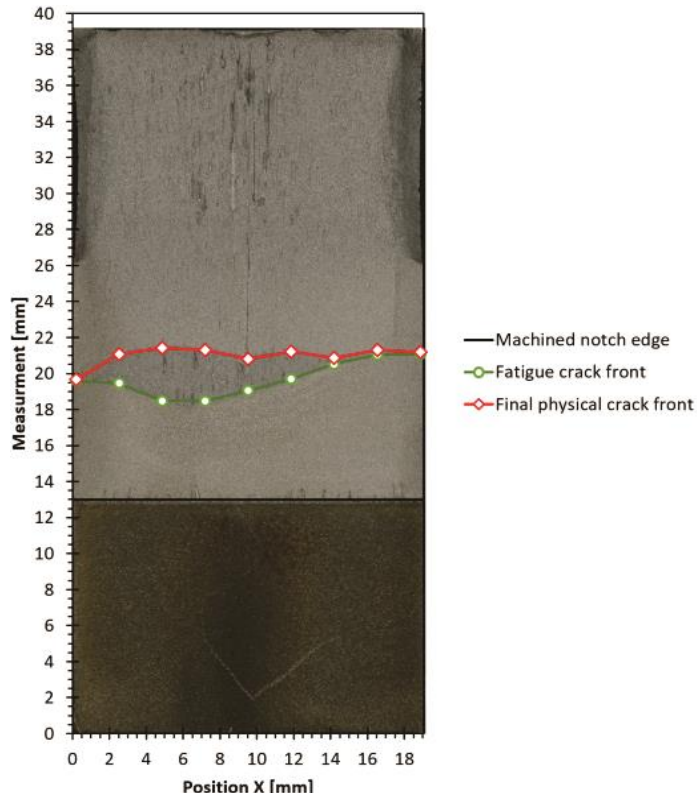


Figure 8. Fracture surface and crack measurement.

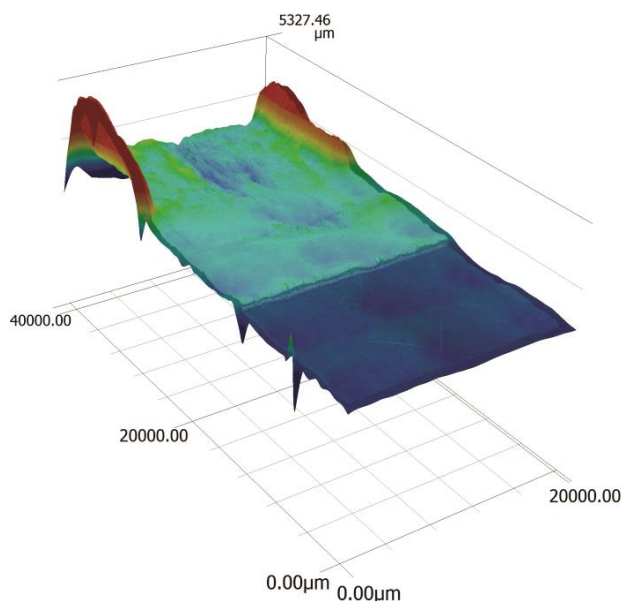


Figure 9. A 3D surface profile of the specimen's fracture surface.

As a result of testing, J - Δa and δ - Δa resistance curves are constructed, as shown in Fig. 10. Fracture mechanics parameters obtained from this experiment are presented in Table 7.

Table 7. Obtained fracture mechanics parameters.

Parameters	Results	Unit
Critical J-integral	J_{IC} 47.36	kJ/m^2
Fracture toughness	K_{IC} 105.64	$\text{MPa}\cdot\text{m}^{1/2}$
Crack tip opening displacement	δ_{IC} 0.0172	mm

Fatigue crack growth rate under cyclic loading is presented in Fig. 11, where data points obtained in the logarithmic plot represent the dependence of fatigue crack growth da/dN on the stress intensity factor range ΔK .

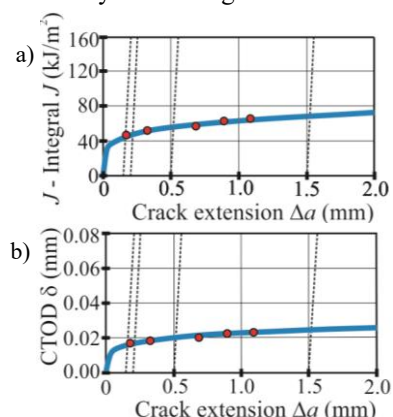


Figure 10. Resistance curves: a) J - Δa ; b) δ - Δa .

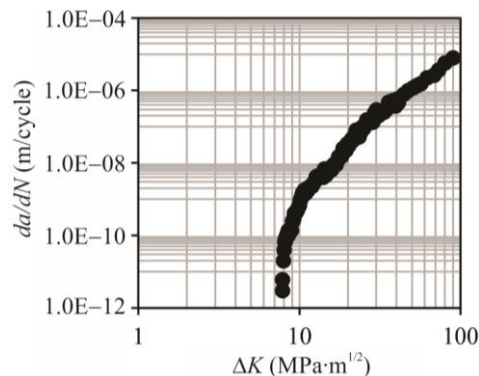


Figure 11. Data points of fatigue crack growth test.

The aforementioned relationship is described by two laws. Figure 12 presents the Paris law, which is characteristic of stable crack growth, while Fig. 13 shows the McEvily law, which also accounts for the threshold for crack propagation. The parameters obtained according to these two laws are presented in Table 8.

Table 8. Parameters of the Paris and McEvily law.

Law	Parameter	Result
Paris	C	$1.043 \cdot 10^{-14}$
	M	4.914
	R^2	0.907
McEvily	C_1	$2.464 \cdot 10^{-10}$
	$\Delta K_{th} (\text{MPa}\cdot\text{m}^{1/2})$	7.87

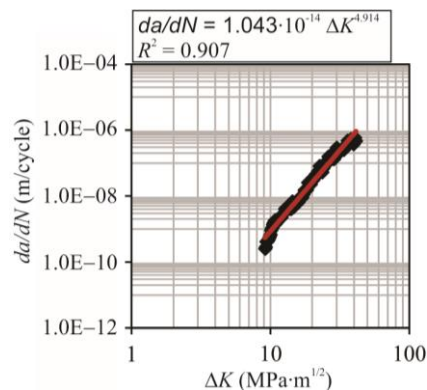


Figure 12. Paris law of fatigue crack growth.

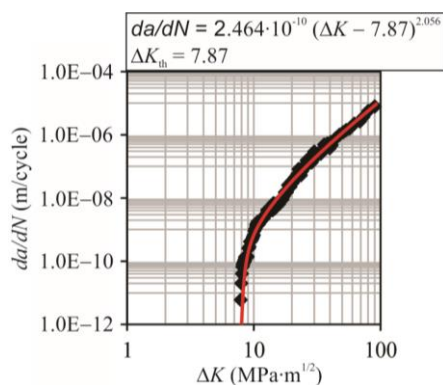


Figure 13. McEvily law of fatigue crack growth.

CONCLUSIONS

In this paper, complete experimental characterisation of armour steel PROTAC 500, produced by heat treatment of quenching with low-temperature tempering at 220 °C, is performed. Microscopic analysis shows that the material has a microstructure of tempered martensite, which is in accordance with the achieved high hardness values. The average measured hardness is 533.5 HV (504 HB), which confirms a high level of resistance to penetration.

Tensile testing determined the mechanical properties of the material: yield strength of 1302 MPa, tensile strength of 1677 MPa, elongation of 11.6 % and cross-section contraction of 52.3 %. The instrumented Charpy test shows that the total impact energy is 32 J (impact toughness is 42.6 J/cm²), where 24.8 J is spent on crack initiation and 7.2 J on its propagation, which indicates a relatively good resistance of the material to fracture under impact loading.

Fracture mechanics analysis determined the resistance curves, based on which key parameters are obtained: critical J-integral 47.36 kJ/m², fracture toughness 105.64 MPa·m^{1/2} and CTOD 0.0172 mm. These results confirm a satisfactory level of material resistance to initiation and stable crack growth. The rate of crack growth under cyclic loading is analysed using Paris and McEvily's law. The threshold for crack propagation $\Delta K_{th} = 7.87 \text{ MPa}\cdot\text{m}^{1/2}$ is determined, while stable crack growth is adequately described by the Paris law.

Based on the conducted tests, it can be concluded that the armour steel PROTAC 500 has an extremely favourable combination of high strength, hardness and satisfactory fracture toughness, with a clearly defined behaviour during fatigue and crack propagation, which fully characterises the material. The obtained results represent a significant basis for its proper dimensioning, service life assessment and safe exploitation in real application conditions.

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